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The Neutrino Program at LAMPF

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LAMPF is an 800-MeV linear accelerator capable of accelerating beams of about 1 mA routinely. This intensity makes it a unique source of neutrinos in the range of tens to a few hundred MeV. The dominant particles produced in the beam stop at LAMPF are π^+; they decay according to the reaction $\pi^+ \rightarrow \mu^+ + \nu_\mu$, producing a copious source of monoenergetic ν_μ from pion decays at rest. The muons stop in the target and in turn decay according to $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$, giving a source of ν_e and $\bar{\nu}_\mu$ with the same overall flux and known "Michel" spectra. The π^- that are produced are all absorbed in a heavy element target such as copper excepting the approximately 1% that decay in flight before coming to rest. The normal beam spill at LAMPF (~ 1msec) is long enough that the neutrino flux is essentially uniform through this spill. Apart from negative pions that decay in flight there are no $\bar{\nu}_e$ produced. The decay-in-flight neutrino spectra peak near 150 MeV so that these two components separate well by the energy of the neutrinos.

There are two neutrino experiments that have ceased taking data; the first experiment (E225) was designed to verify the interference between charged and neutral current amplitudes in ν_e- e scattering. The experiment was situated at 90° to the beam stop, and detected recoil electrons from neutrino electron scattering.(1) The experiment was sensitive to recoil electrons from ν_μ, ν_e, $\bar{\nu}_\mu$ but the cross section for ν_e - e scattering is the dominant contribution. The magnitude of this cross section depends on the size of the interference term between charged and neutral current scattering, and the value for this term is $-1.07 \pm 0.017 \pm 0.11$ to be compared to -1.08 from standard electroweak theory with $\sin^2\theta_W = 0.23$. The observation of this interference is unique to this experiment.

The second experiment (E645), which is presently finishing data analysis after concluding data taking in 1989, was a search for neutrino oscillations of the type $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.(2) The experiment was designed to search for the reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n \ ,$$

which has a large relative cross section compared to that on complex nuclei due to the absence of Pauli Suppression of the reaction on free nucleons producing electrons in the energy range 30 - 50 MeV in contrast to the dominant background from

$$\nu_e + {}^{12}C \rightarrow e^+ + {}^{12}N$$

in which the electron energies are limited to 30 MeV from the Q value of the reaction. The present limits in the published literature are shown in Fig. 1 together with results from comparable experiments.

An experiment, which has been proposed at LAMPF, extends the search of the previous experiment.(3) The previous experiment has proved to be background free, and the sensitivity was limited only by statistical considerations. A primary difficulty with these experiments is the presence of cosmic rays causing event signatures in the detector, which simulate oscillation events. A prime example occurs when a μ^+ stops in the detector and gives rise to a decay electron with an energy up to 50 MeV. A "veto" shield is used to detect the parent cosmic ray muon with an efficiency differing from unity by a few parts in 10^6. A picture of this muon shield is shown in Fig. 2. The experiment E645 used a conventional tracking detector inside this veto shield to detect the secondary electrons from neutrino interactions. The new proposal intends to use a liquid scintillator detector with extensive phototube coverage to reconstruct candidate events. This detector has a greater density and a more nearly complete acceptance, so that the sensitivity of the experiment to oscillation is improved accordingly. The experiment will be situated in the same location as is shown in Fig. 3. Figure 4 shows the shielding around the detector location so that the hadronic component of cosmic rays is completely shielded from the detector. The internal detector is remarkably simple in concept as is shown in Fig. 5. Two components are vital however. The phototubes that are to be used to detect the light from neutrino events have to be large in area for reasons of economy, and must detect single photoelectrons efficiently and with precise timing. In Fig. 6 is shown a prototype of these tubes developed by Burle Industries[4] and tested by Los Alamos. These tubes are not only sensitive to single photoelectrons but yield a spectrum as in Fig. 7. The single photoelectron peak is immediately obvious with a substantial valley between this peak and thermal noise. The two photoelectron peak is also visible and higher numbers of photoelectrons may also be resolved under increased magnification. The timing resolution of these single photoelectrons has also been measured to have a sigma of 1.2 ns. This performance allows a detector to be designed in which the neutrino induced reactions may be detected with high efficiency, with angular resolution largely limited by multiple scattering as in Fig. 8a and position resolution close to 10 cm as in Fig. 8b.

A second feature of this experiment is the use of a dilute mixture of liquid scintillator and mineral oil. This allows separation of cherenkov light and scintillator light by timing. The dilute scintillator yields about 1/30 of the light normally achieved in liquid scintillator and then has a decay constant somewhat longer than normal. Tests have been made that demonstrate an ability to discriminate between the cherenkov ring and the scintillation light, which is emitted isotropically and later in time. At a deposited energy that corresponds to a 40 MeV electron, a rejection between electron and proton of 10^3 is expected. The signature reaction for oscillations is

$$\bar{\nu}_e + p \rightarrow e + n ,$$

which has a neutron in the final state. It is proposed to detect this neutron by observation of the 2.2-MeV γ ray in the neutron capture on a free proton

$$n + p \rightarrow D + \gamma .$$

The neutron thermalization time and the expected signal from the γ ray are shown in Fig. 9. In Fig. 10 is shown the signal for neutrino mixing between $\bar{\nu}_e$ and $\bar{\nu}_\mu$ of 5×10^{-4} together with expected values of the dominant backgrounds. The probability (or limit) for oscillation is then extracted by a fit to the composite distribution giving an expected limit shown in Fig. 11, together with relevant data from previous experiments.

Although a beam stop is not expected to be a prolific source of decay in flight neutrinos, the beam stop at LAMPF contains about 1% pion decay in flight. The overall flux is sufficiently high that a substantial number of events from neutrinos that are generated by pions that decay in flight is expected in a two year running period. Moreover this energy range $\nu_\mu > 50$ MeV is expected to have very small background as has already been observed in E645 at a reduced level. A search for high energy (>50 MeV) electrons yields a neutrino oscillation sensitivity shown in Fig. 12 together with the limits from decay at rest neutrinos from the beam stop and PSR.

The major thrust of the neutrino program at LAMPF is an experimental facility, which has been referred to as the Large Cherenkov Detector (LCD).[5] The experiment is proposed to measure the ratio

$$R = \sigma(\nu_\mu - e) \; / \; (\sigma(\nu_e - e) + \sigma(\bar{\nu}_\mu - e)) \quad . \tag{1}$$

The H^- beam from LAMPF is injected into a proton storage ring (PSR). This beam is then extracted in a single turn giving a pulse 250 μs long. This pulse is targeted to produce pions in a beam stop configuration as in the other experiments described above. The recoil electrons are detected in a large water cherenkov detector with the same phototubes as detectors for cherenkov light alone much as the the experiment described above, LSND. The numerator in eq. 1 is identified by the neutrino events that occur in the time that the proton beam is being targeted. The denominator in eq. 1 is associated with the events that appear after the proton pulse with the characteristic lifetime of the muon (2.2 μsec). Many of the systematic errors disappear in taking the ratio of these combinations of cross sections, and it is believed that a measurement of this ratio to 2% will yield a value of $\sin^2\theta_W$ accurate to 1%. With the extraordinarily precise measurements of the Z mass at LEP and SLC, this measurement constitutes a determination of the electroweak radiative corrections, which are sensitive to the mass of the top quark and to a lesser extent to the mass of the Higgs. This measurement is seen then as a cornerstone to the testing program of the electroweak theory in the coming decade. The electron-scattering reaction is identified by the forward peak in the direction of the recoil electron and the incoming neutrino. The only substantial background comes from the reaction

$$\nu_e + {}^{16}O \rightarrow e + {}^{16}F \; .$$

In Fig. 13 is shown the quality of data that is expected after four years of data taking with the forward peak distinctly visible. In Table I is shown a list of systematic errors that at this time are believed to be the ultimate limit of precision of this experiment.

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1. R. C. Allen et al. *Phys. Rev. Lett.* **55**, 2401 (1985); R. C. Allen et al., Los Alamos National Laboratory document LA-UR-89-3723.

2. L. S. Durkin et al., *Phys. Rev. Lett.* **61**, 1811 (1988).

3. Burle Industries, Inc., Lancaster, PA.

4. A Proposal to Search for Neutrino Oscillations with High Sensitivity in the Appearance Channels $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$, Los Alamos National Laboratory document LA-UR-89-3764 (1989).

5. A Proposal for a Precision Test of the Standard Model by Neutrino-Electron Scattering. Los Alamos National Laboratory report LA-11300-P (1988).

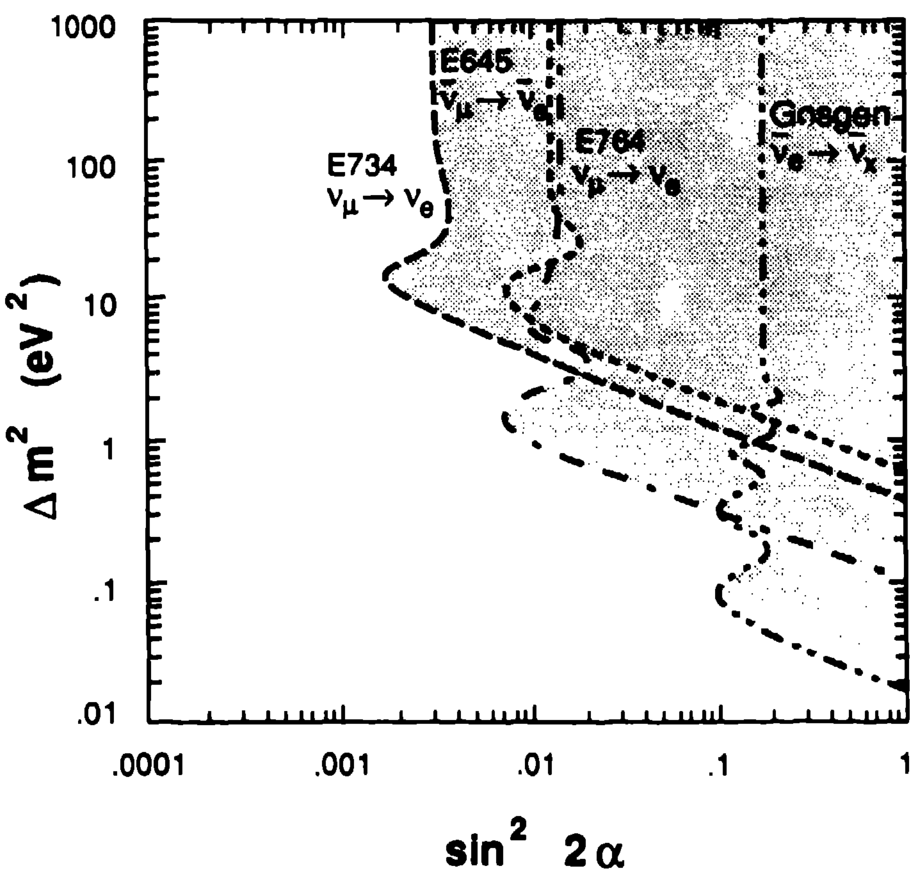


Fig. 1 Limits on $\sin^2 2\alpha$ and Δm^2 from recent experiments including the published result from LAMPF experiment E645.

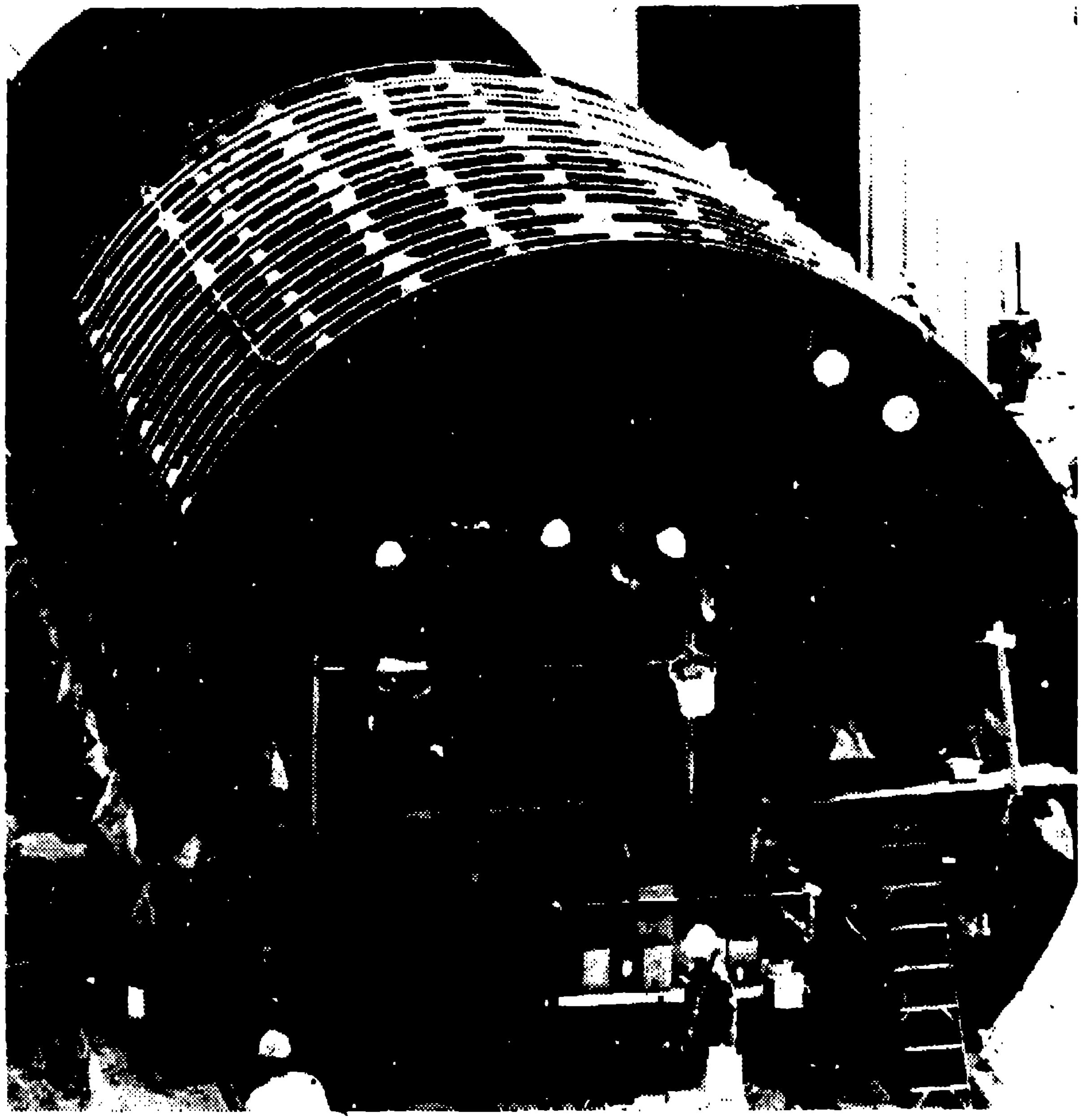


Fig. 2 The Cosmic ray muon shield for E645 and for the proposed neutrino oscillation experiment LSND.

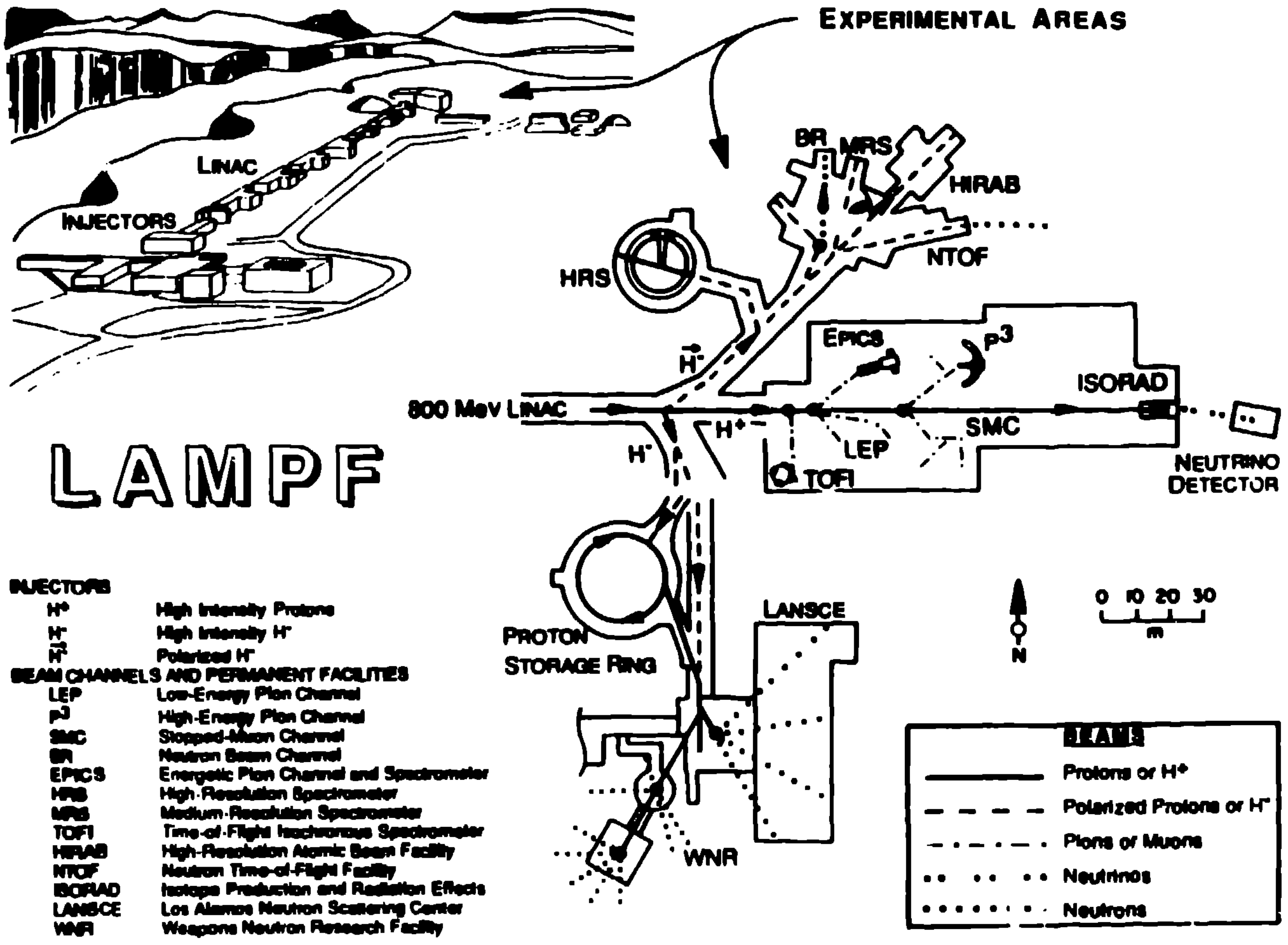


Fig. 3 Layout for the experimental area at LAMPF including the A6 beam stop.

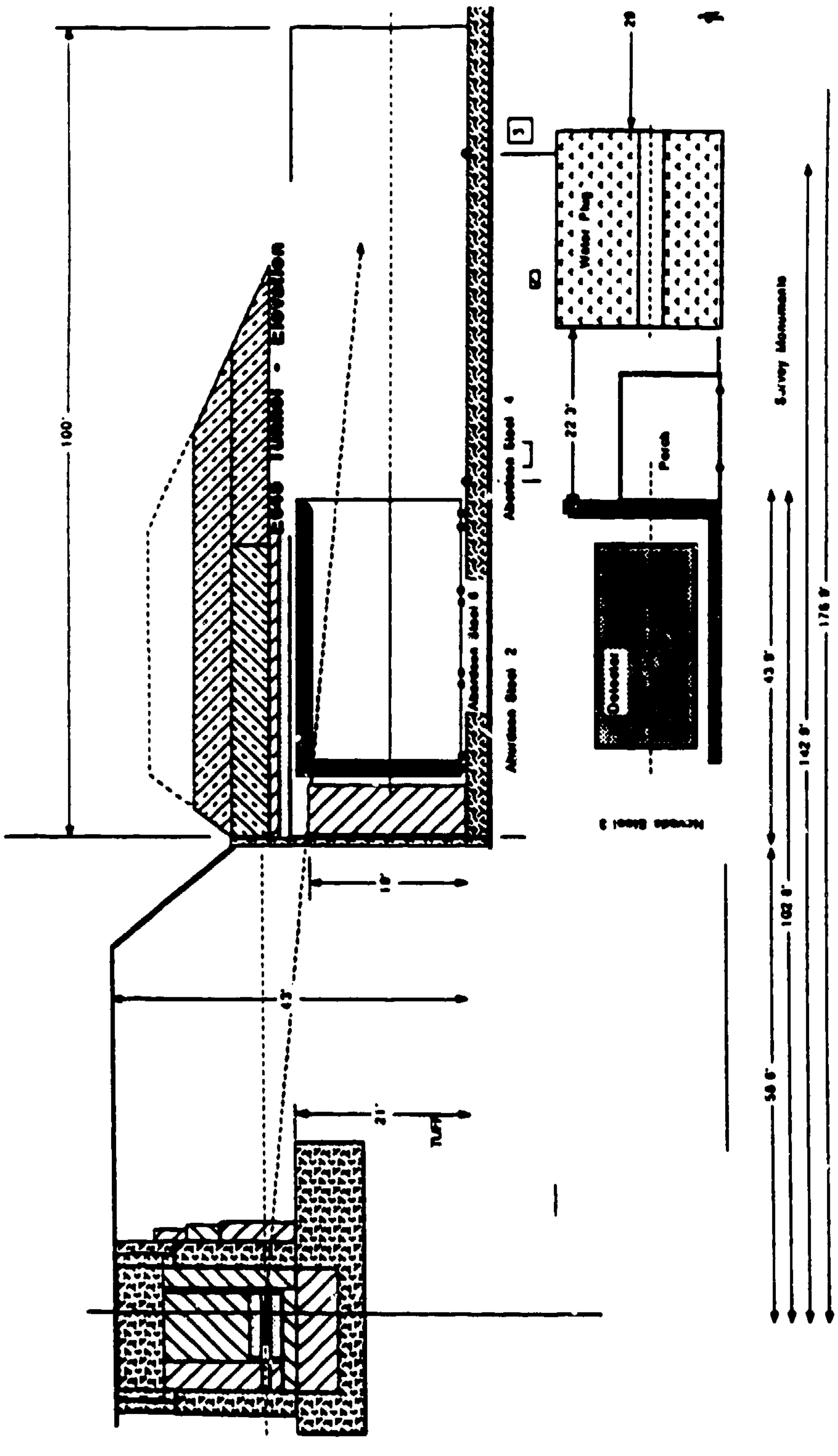


Fig. 4 Shielding for the neutrino area at the LAMPF beam stop.

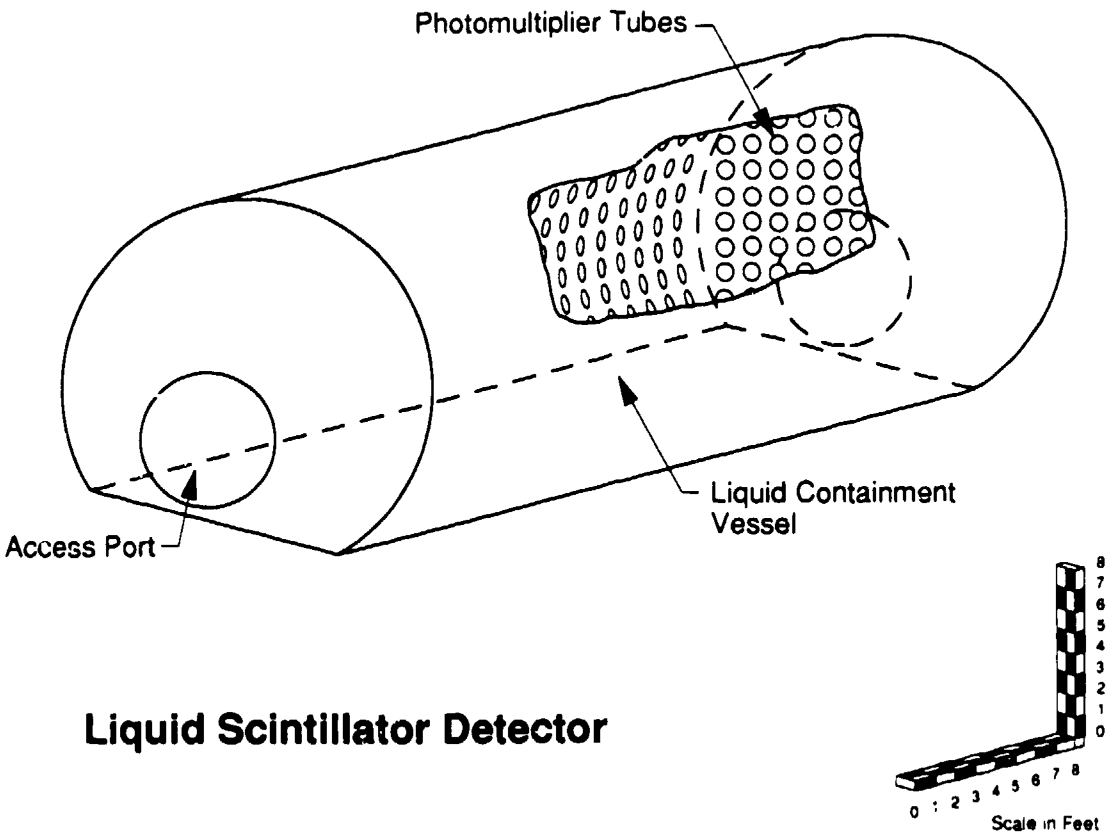


Fig. 5 A schematic for the Liquid Scintillator Neutrino Detector (LSND).

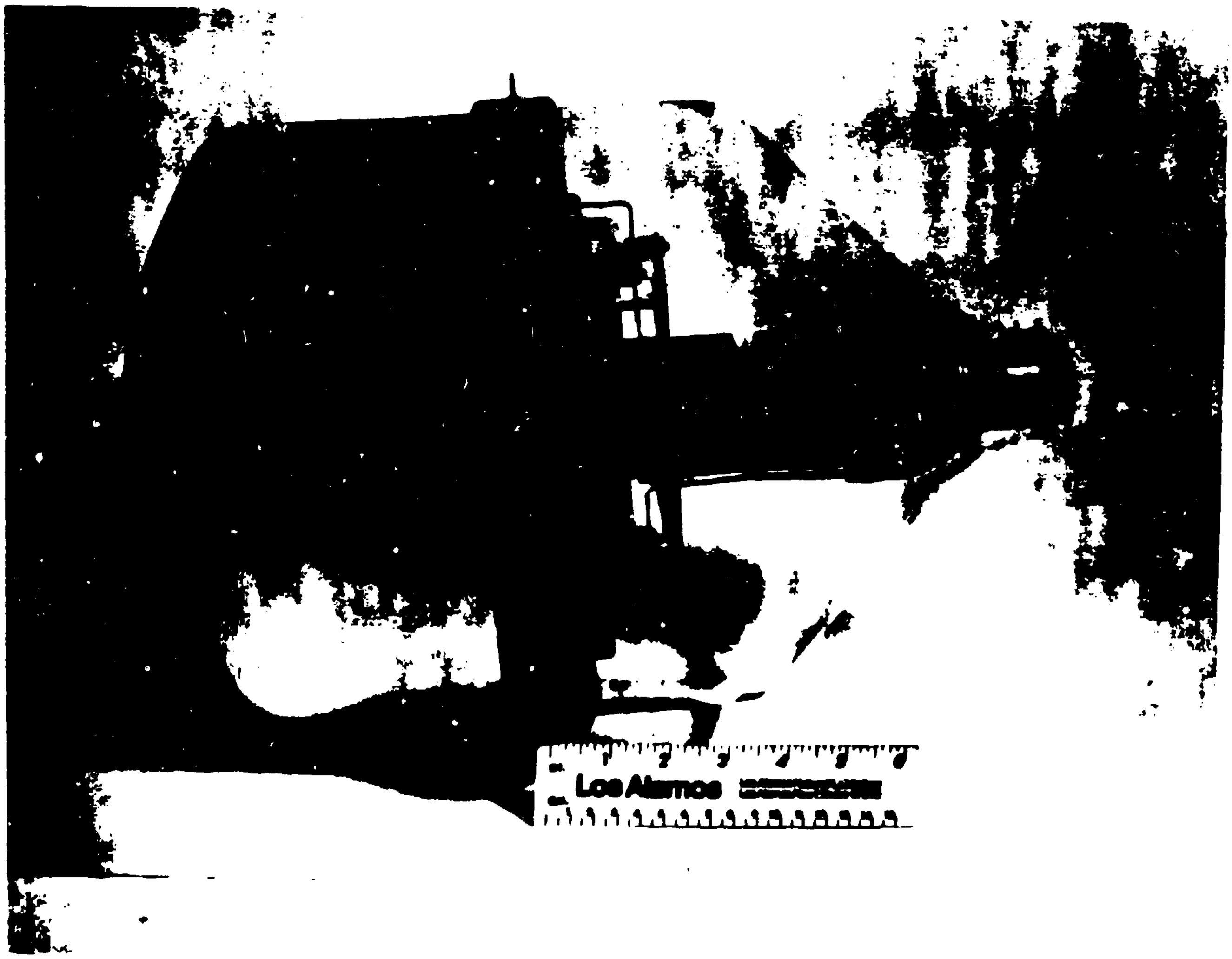


Fig. 6 Prototype photomultiplier from Burle Industries.

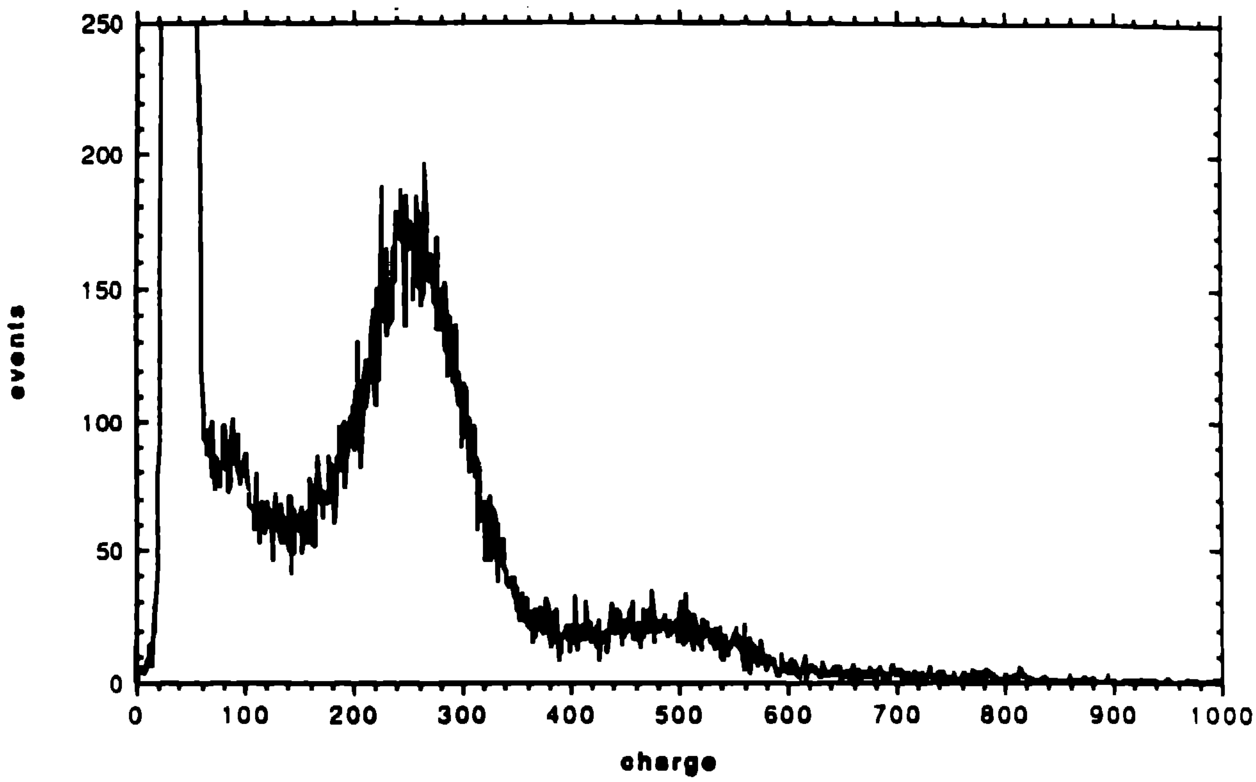
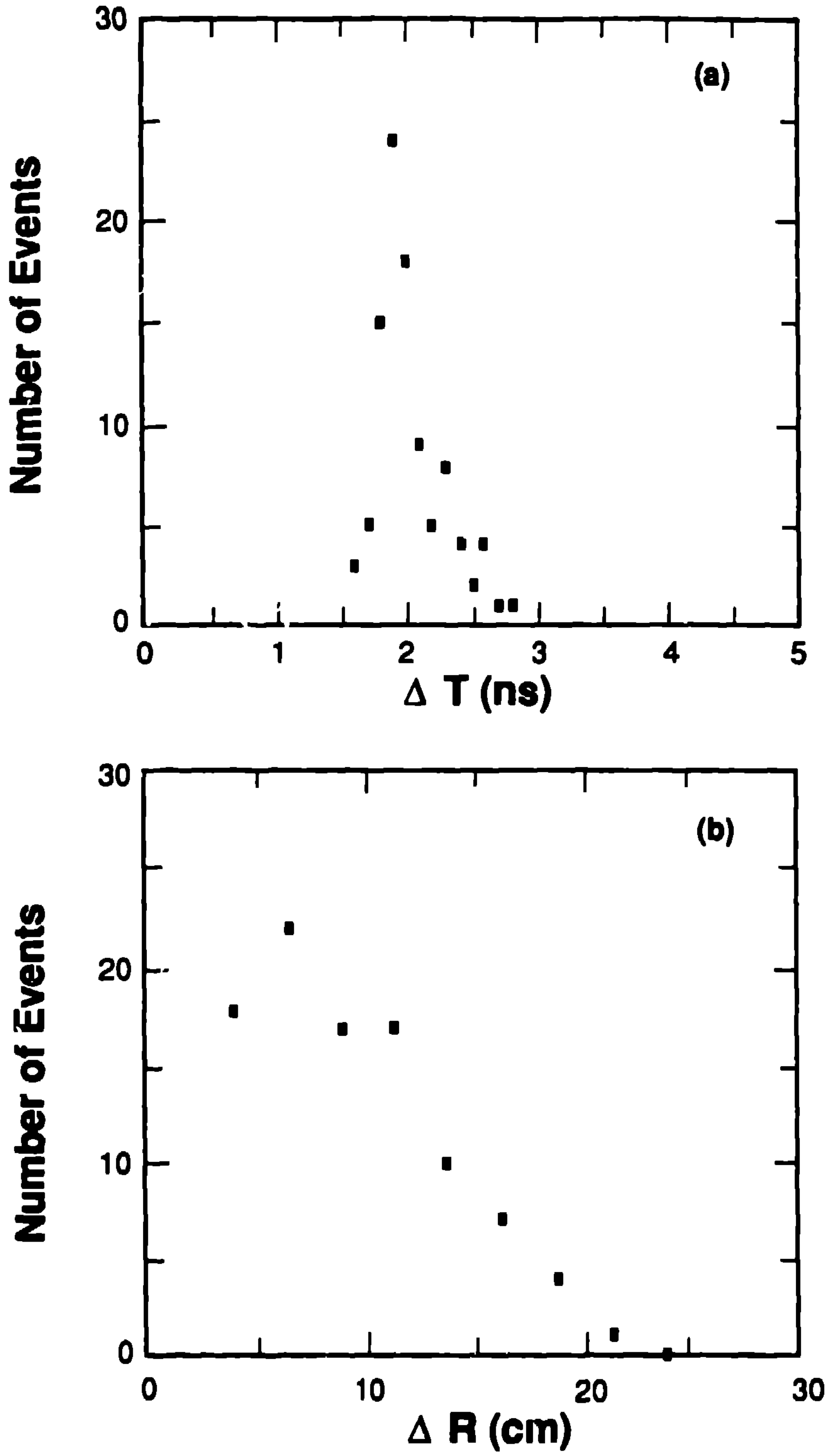


Fig. 7 Low-light intensity spectrum of Burle tube showning one and two photoelectron peaks.



Figs. 8a,b The (a) time and (b) position electron resolution functions for a sample of 45 MeV electrons. The time resolution is approximately 0.21 ns, and the average error in position is 9.3 cm.

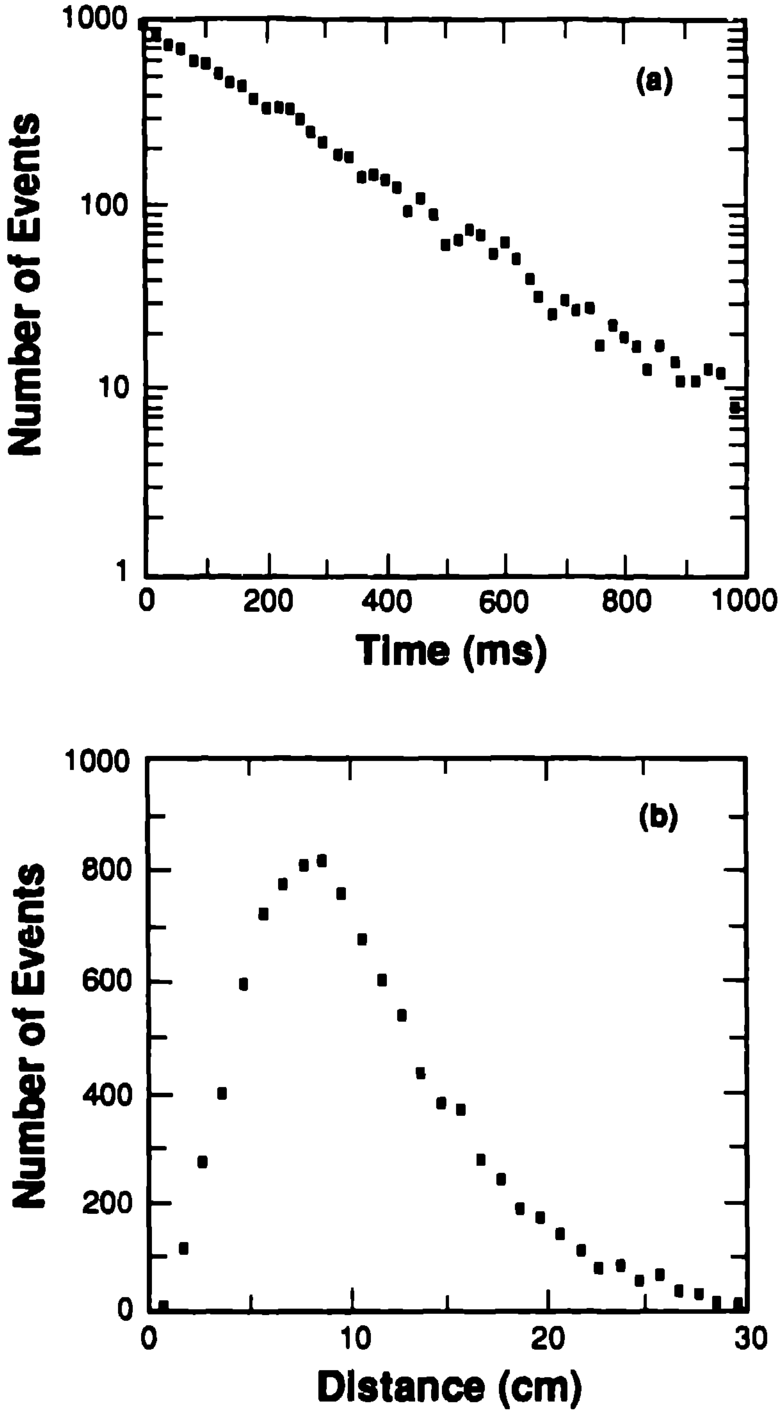


Fig. 9a,b The (a) capture time and (b) straight-line distance travelled for a large sample of recoil neutrons from $\bar{\nu}_e p \rightarrow e^+ n$ interactions. The mean neutron capture time is 203 μs and the average straight-line distance travelled by the neutron before capture is about 10 cm.

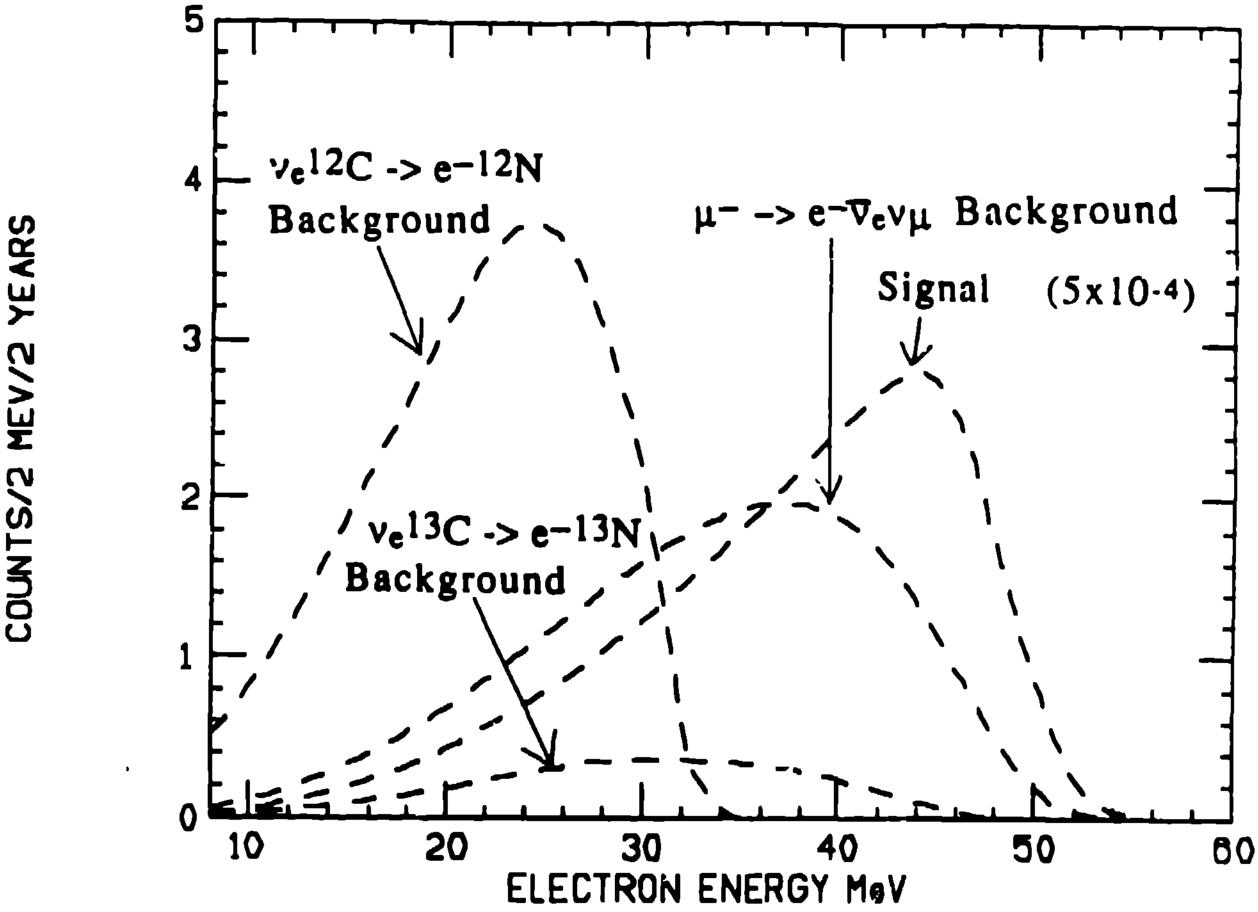


Fig. 10 The expected positron energy distributions from $\bar{\nu}_e p \to e^+ n$ events for $\bar{\nu}_e$ from $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations and μ^- decay at rest background. Also shown are the expected electron energy distributions from the backgrounds $\nu_e\,{}^{12}C \to e^-\,{}^{12}N$ and $\nu_e\,{}^{13}C \to e^-\,{}^{13}N$.

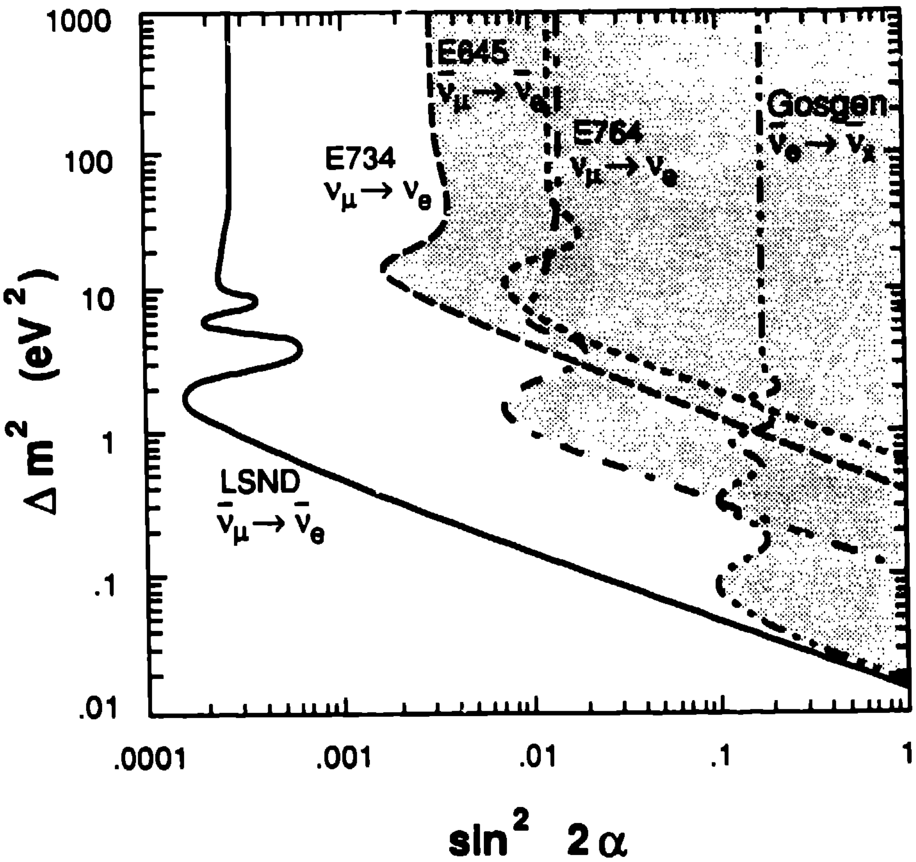


Fig. 11 The present $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation limits from reactor (Gosgen), BNL (E734), and LAMPF (E645) experiments expressed in terms of the Δm^2 vs $\sin^2 2\alpha$ two parameter space. The oscillation probability is expressed as $p_{\bar{\nu}_\mu \rightarrow \bar{\nu}_e} = \sin^2 2\alpha \sin^2 [\Delta m^2 R/4E_\nu]$, where α is the mixing angle, $\Delta m^2 = m^2_{\bar{\nu}_\mu} - m^2_{\bar{\nu}_e}$, R is the neutrino propagation distance, and E_ν is the neutrino energy. Also shown is the limiting curve expected from this proposal with neutrinos from μ^+ decay.

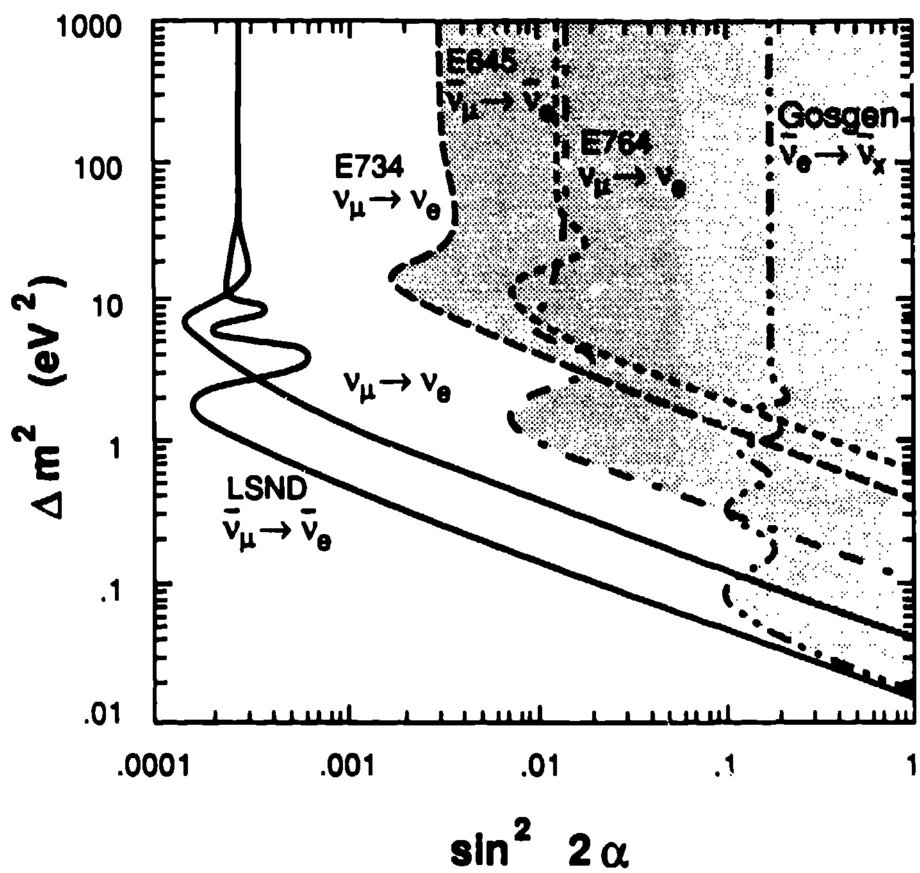


Fig. 12 The expected $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation limits from LSND proposal, expressed in terms of the Δm^2 vs $\sin^2 2\alpha$ two parameter space.

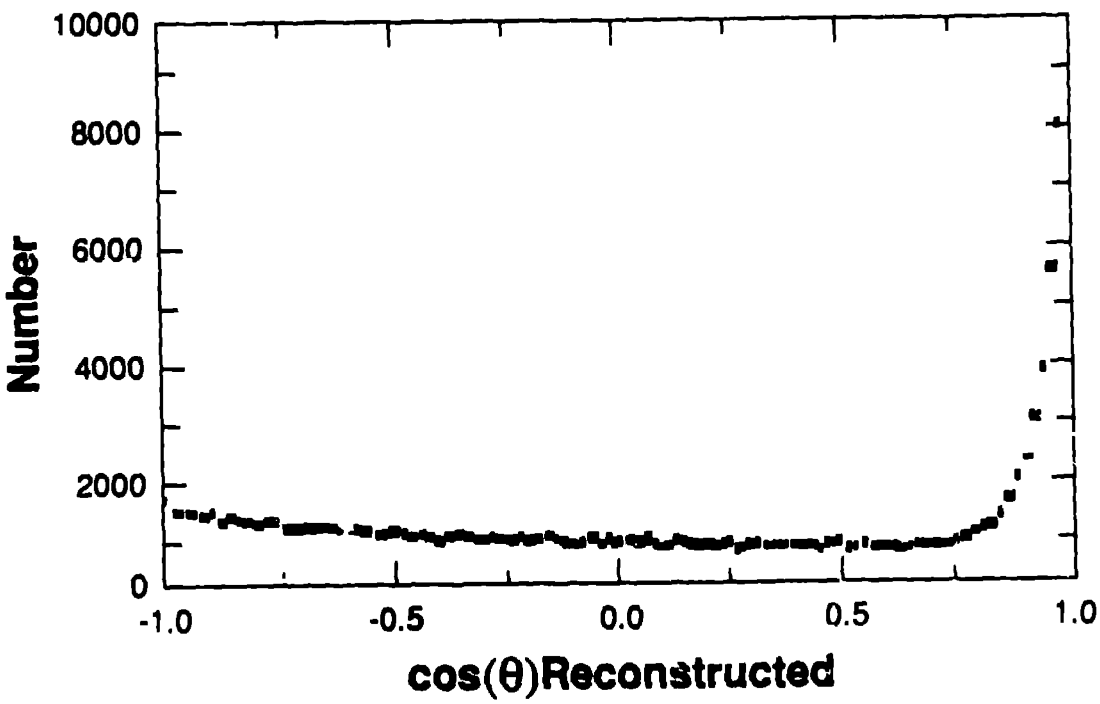


Fig. 13 The reconstructed angular distribution of ν-e and ν-O events combined.